Quantum computing based on superconducting charge qubits

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Introduction

The proposal of quantum information processing has shown us the first serious possibility, though still limited in the range of applications, to break away from the traditional spell that has been bounding the integration scale of the electron device and its processing power for a long time. Qubit (quantum bit), the basic element of the quantum information processing, consists of a quantum two-level system that can be brought to a superposition by an external mean. Among the numerous possible two-level systems, various typical microscopic two-level systems such as polarized photon states, atomic states and nuclear spins states have been utilized first to demonstrate the realization of the quantum calculation. However, to realize a scaled-up version of the quantum computing system consisting of hundreds of qubits, a solid state electronics version of it is considered to be perhaps indispensable. We demonstration first electronic control of 1-qubit achieved in a solid state device. The general scalability of such a solid state device is considered to be a prerequisite for a practical quantum computer of the future.

Single-Cooper-pair box

We utilized a submicron electron device called a single-Cooper-pair box, to demonstrate the operation of 1-qubit control in solid state electron device. It is a small superconductive box connected to the outside by a Josephson tunnel junction and a gate capacitor. Cooper pair can tunnel into the box through the tunnel junction. However, due the small capacitance C of the box, the transfer of the Cooper pair would be accompanied by a large gain in charging energy, making the transfer of the Cooper pairs energetically difficult at low bias voltage. When the charging energy E_c associated with the transfer of one electron charge across the tunnel junction, $E_c = e^2/2C$, is smaller than gap energy of the superconductor Δ, the transfer of the quasi-particle can be ignored during the gate operation. The large resistance associated with the tunnel junction suppresses the quantum fluctuation of the charge of the box through the junction, thus the number of Cooper pairs in the box is quantized under a certain gate bias voltage. There are many (typically 10^8 in our experiment) Cooper pairs in the box, but they form a single macroscopic quantum charge-number state, corresponding to the number of excess electrons in the box.

Fig1 shows the energy diagram of the system. The energy difference between the upper and lower band are $\Delta E = \sqrt{E_J^2 + \delta E^2}$, where $\delta E = 4E_C(Q/e-1)$ and $Q = C_g V_g$. Josephson coupling enables a dissipation-less transfer of an electron pair, thus two neighboring charge-number states, designated as a state $|0\rangle$ and a state with one more Cooper-pair $|1\rangle$ can be coherently coupled. This was achieved by biasing the box at $Q = e$, the resonant condition, by gate, or by using photon assisted coupling of two states at the off resonant condition where $Q \neq e$ (Fig1). In this way one can create an artificial two-level system.

The result of previous experiments showing that the macroscopic quantum state of superconductivity is extraordinary well isolated from the internal and external dissipation [1] gave us a confidence in such experiment that requires an extremely low dissipation. For the detection of the quantum state, we attached an additional tunneling probe to the box, our original method, to study this two-level system. With this probe, we could simply measure the current it carried to monitor the probability of one of the two states that was involved in the coherence.

Device

The typical device picture is shown in Fig2 (the photograph and the schematic diagram). The whole structure was made of aluminum thin film (t ~ 20nm). The box has a dimension of 700nm x 50nm, a size quite comfortably reproducible by an electron beam lithography. The coherence junction, with which quantum coherence was prepared, was split into two junctions, forming a SQUID loop. In this way we could control the Josephson energy of the system with an external magnetic field, an extra leverage that was probed to be quite useful as discussed below. The tunnel junction was prepared by the angle evaporations through the suspended stencil mask. The thickness of the tunnel barrier, natural oxide of aluminum, was controlled by regulating the partial pressure of the oxygen of the evaporation chamber. The probe junction had thicker tunnel oxide, prepared by an additional oxidation process, and typically resulted with a resistance roughly three orders of magnitude lager compared to the coherence junctions. To couple a wide bandwidth electric signal to the box, a high-speed gate was made employing a coplanar wave-guide design (50Ω). The entire device was made on top of a copper ground plane, with silicon nitride insulating layer in between. The typical Josephson energy of the coherent junction was ~40μeV, the charging energy of the box was typically ~100μeV. The experiments were carried out at an environment with a low thermal energy, typically ~30mK or 3μeV, low enough compared with all relevant energies associated with the box.

Energy-domain experiment

We studied the two-level system by two complimentary experiments, an energy-domain spectroscopic experiment [2] and a time-domain quantum oscillation experiment [3]. First, we performed the energy-domain experiment, utilizing a photon assisted tunneling method. We attached an additional tunneling probe to the box to study this two-level system. At the resonant condition, there was a resonant current flowing into the probe junction within the Coulomb blockade region, when the probe junction was appropriately biased. This was the current carried by the so-called Josephson-quasiparticle peak (JQP) resonant cycle [4]. The JQP current signifies the cyclic production of a coherence state between states $|0\rangle$ and $|1\rangle$, followed by decoherence of the coherence state due to transfer of two qusiparticles to the probe electrode.

The aim of this experiment was to trace out the upper energy band as shown schematically in Fig1. To carry out this feat, we utilizing a photon assisted tunneling method. Even at the off-resonant bias condition, if there is photons with appropriate energy, the states $|0\rangle$ and $|1\rangle$ can also be coupled. This photo-assisted coupling resulted with appearance of a photon-assisted JQP peak current at the corresponding off-resonant gate bias. By sweeping the photon frequency while varying the gate bias, we obtained a series of photon-assisted JQP structures that traced out the upper energy band of the system. When the resistance of the probe junction was sufficiently high (sufficiently small dissipation in observation), the experiment showed a clear band gap structure in the eigenstates as shown in Fig3 [2]. The existence of the gap at the degeneracy condition of states $|0\rangle$ and $|1\rangle$ signifies the existence of quantum coherence between this two states. This was the first time such gap was observed directly by spectroscopic technique, although some indirect evidences of such gap were reported previously [5,6].

Time-domain experiment - Qubit

To further study the coherence, we carried out a bolder experiment designed to observe the dynamics of the coherence, namely, the coherent oscillation. First, as the initial state, we prepare a pure state $|0\rangle$ by biasing the system far from the resonant condition. Next, we applied a sufficiently fast voltage pulse to the gate (a non-adiabatic gate operation) to create a degenerated charge-number state at the resonant condition. The voltage rise time has to be fast enough to initiate a non-adiabatic transition [7]. At the degenerate point, two neighboring charge states $|0\rangle$ and $|1\rangle$ were coherently coupled by the Josephson energy, so that the two states were force to undergo a quantum oscillation during the time Δt that correspond to the gate pulse width. At the end of pulse the system was brought back to the original bias point, but at this moment, the state of the system contained a coherent superposition of states $|0\rangle$ and $|1\rangle$.

At this point, we carried out a sampling measurement of state $|1\rangle$ by the attached probe junction. This was done by measuring the current carried by the probe junction under the repeated pulsing experiments. Under an appropriate voltage bias condition of the probe junction, the $|1\rangle$ state would decay to $|0\rangle$ state by emitting two quasi-particles (electrons) to the probe electrode with an observation rate Γ(the tunneling rate of the probe junction). It was important to keep the observation "week", namely, $\hbar\Gamma < E_J$, so that the quantum coherence would not be destroyed easily by the existence of the probe junction. The time delay between the pulses was set longer than the measurement time $1/\Gamma$, so the each measurement was independent of the previous one. As a result, the current we monitored corresponded to the averaged probability of the $|1\rangle$ state after sampling for many events (about one million events in the actual experiment). The samplings were carried out at different Δt conditions that resulted with different liner combinations of states $|0\rangle$ and $|1\rangle$. By sweeping Δt with an increment of 1ps or so, we succeeded in tracing out the time evolution of the quantum oscillation (Fig4). The period of the oscillation in this case should be $\hbar/E_J$.

We could control the effective Josephson energy E_J by applying an external magnetic field to the DC SQUID as shown in Fig2. As a result, the period of the oscillation was modulated as anticipated. The Josephson energies obtained from the oscillation periods and the photon-assisted spectroscopy agreed extremely well under all the magnetic field values tested, and they were also modulated by magnetic field exactly as expected, as shown in the inset of Fig4. This was the first time that the quantum coherent oscillation was observed in a solid state electron device whose quantum states involved a macroscopic number of quantum particles. By adjusting *Δt* of the pulse, as well as the strength of the magnetic field, one can achieve the generation of any desired linear superposition of the two states, or the 1-qubit control operation.

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References

[1] J.S. Tsai, A.K. Jain, and J.E. Lukens, Physical Review Letters, 51, 316, 1983

[2] Y. Nakamura, C.D. Chen, and J.S. Tsai, Physical Review Letters, 79, 2328, 1997

[3] Y. Nakamura, Yu. A. Pashkin, and J.S. Tsai, Nature, 398, 786, 1999

[4] T.A. Fulton, P.L. Gammel, D.J. Bishop, L.N. Dunckleberger, G.J. Dolan, Physical Review Letters, 63, 1307, 1989

[5] V. Bouchiat, D. Vion, D. Esteve, M.H. Devoret, *Quantum Devices and Circuits*, Edited by K. Ismail, S. Bandyopadhyay, and J.P. Leburton (Imperial Collage Press, London, 1997), p. 204

[6] L.S. Kuzmin, D.B. Haviland, Physical Review Letters, 67, 2890, 1991

[7] J. R. Rubbmark, M. M. Kash, M. G. Littman, and D. Kleppner, Physical Review A, 23, 3107, 1981